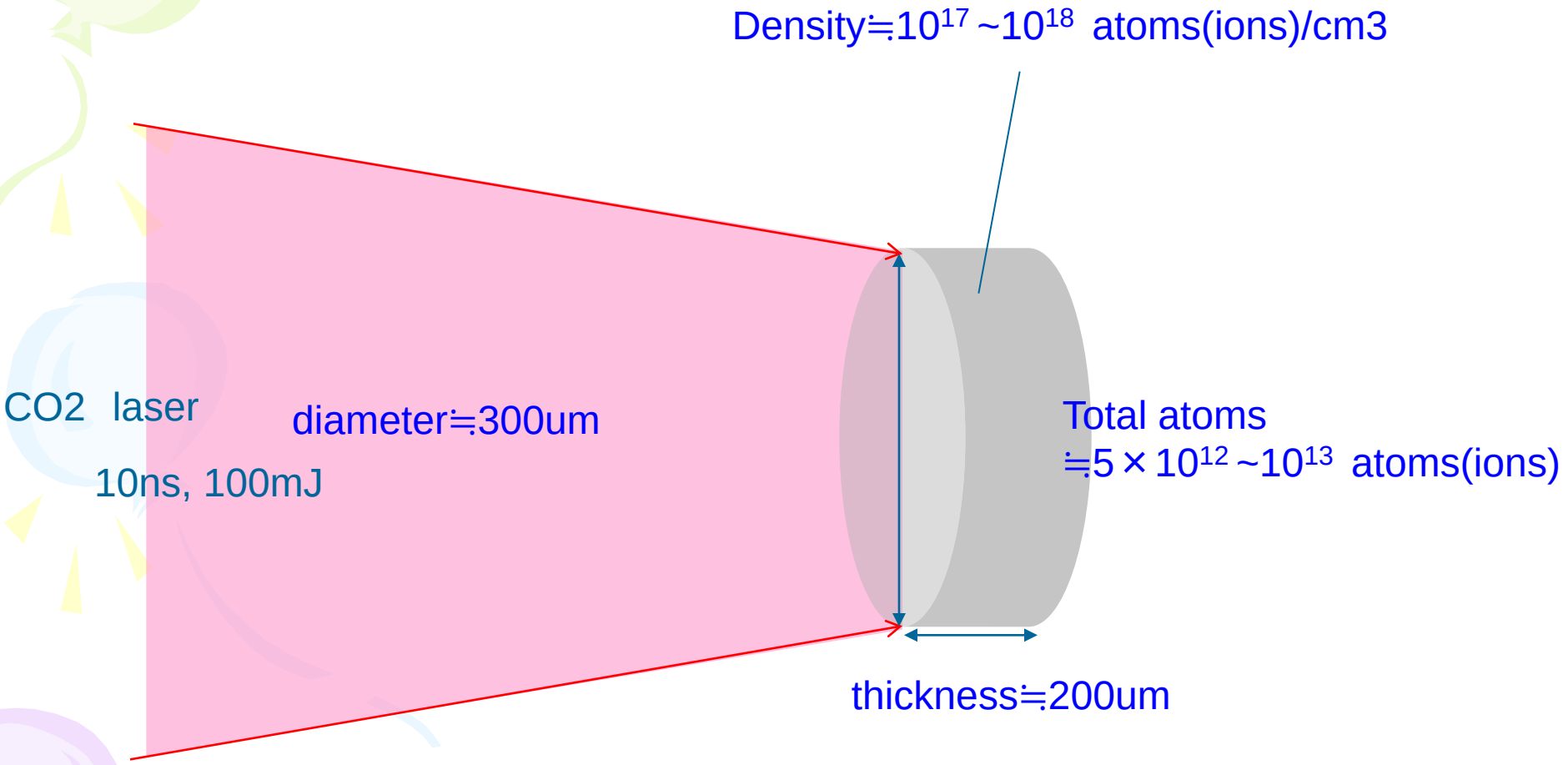
Physical aspects of pre-pulsed tin droplet in transport magnetic field

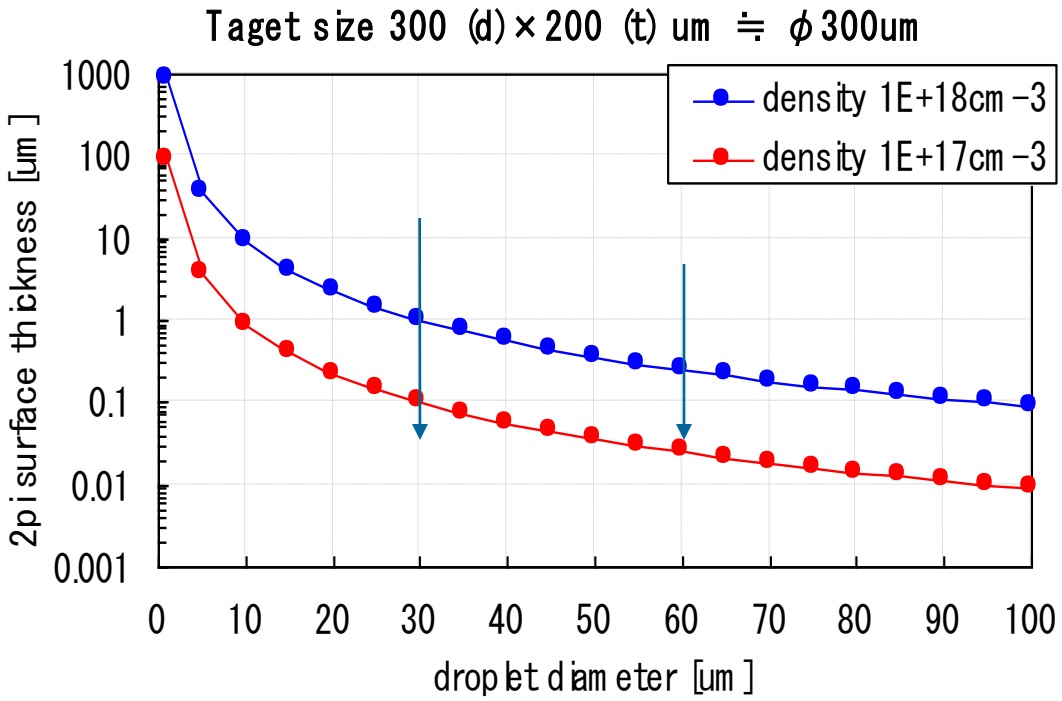
Akira Endo
Waseda University

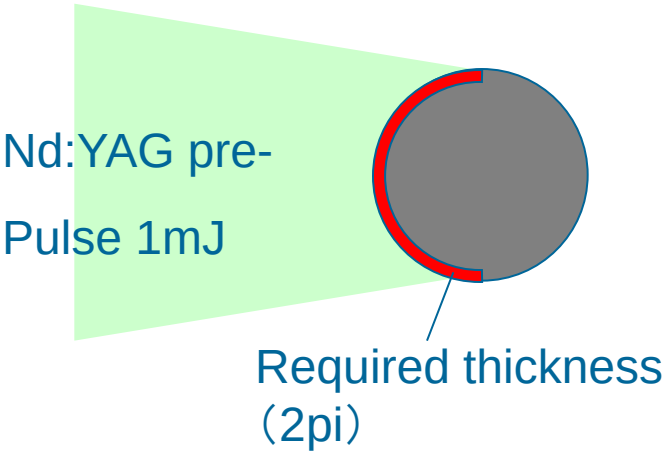
November 8, 2011 Dublin Ireland

Ideal Sn target



Required atoms and droplet surface（2pi）atoms





30um droplet : 0.1～1um（density 10^{17}～10^{18}）

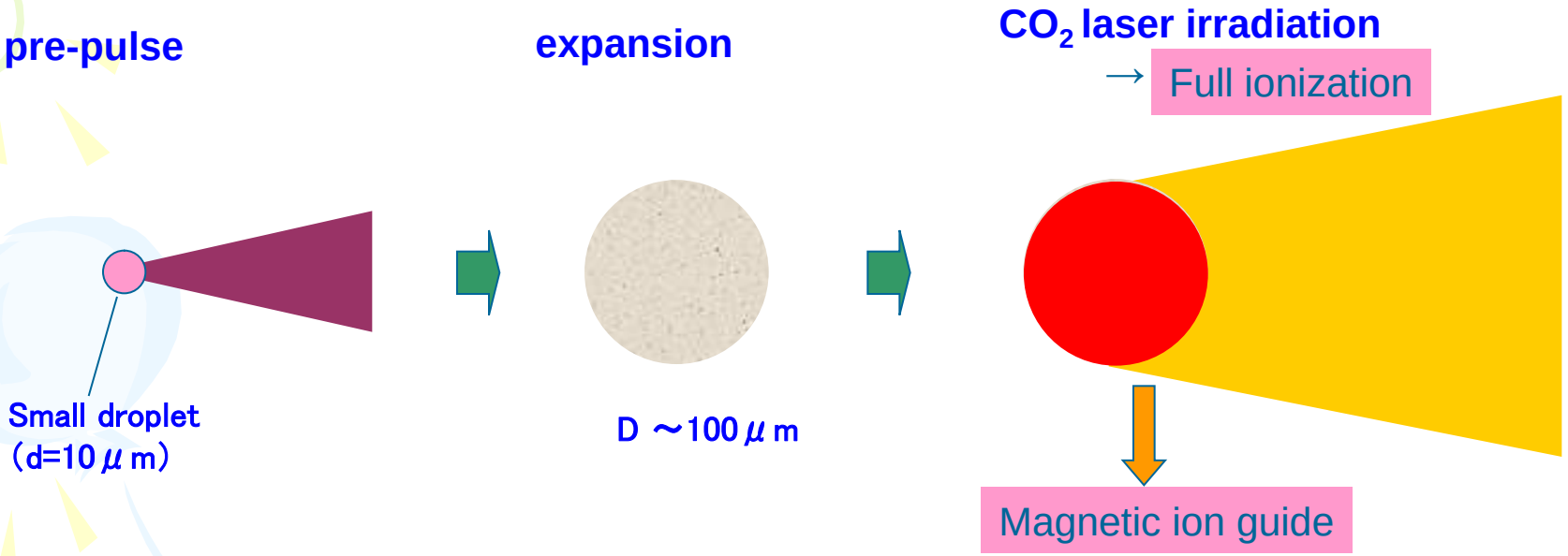
60um droplet : 0.025～0.25um（desnity 10^{17}～10^{18}）

Number of included atoms

Droplet Dia. (um)	Sn	Xe
10	1.9×10^{13}	7.0×10^{12}
20	1.6×10^{14}	5.6×10^{13}
30	5.2×10^{14}	1.9×10^{14}

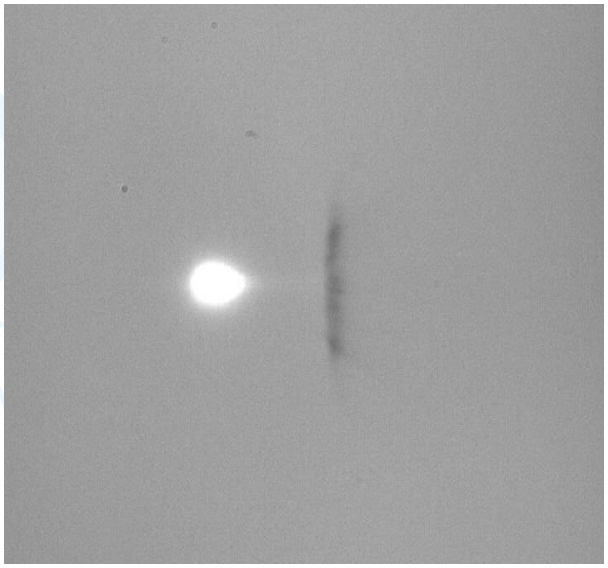
Atomic weight: Sn 118.7 Xe 131.3

Optimization of pre-plasma conditioning

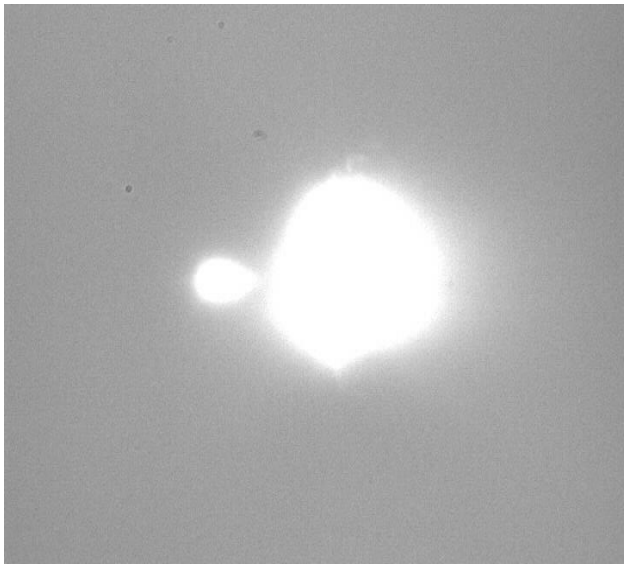


Optimize density, temperature and spatial distribution
for main pulse heating to achieve high EUV conversion efficiency
and **full exhaust of Sn atoms**

Droplet with pre-pulse irradiation



Without main pulse



With main pulse

Data by Gigaphoton Inc

Dynamics of Sn droplet after pre-pulse irradiation

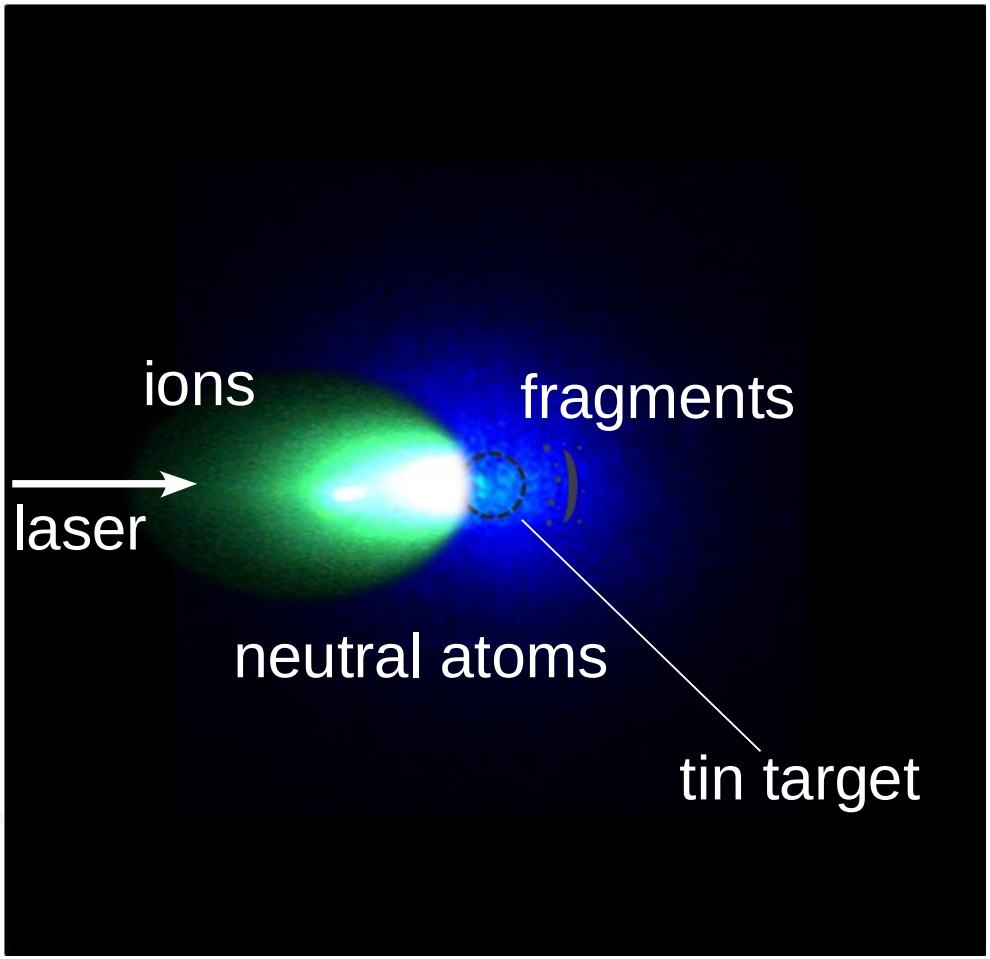
Droplet: spatially and electrically isolated object

Ablation

Spallation

Fragmentation

vaporization



Liquid droplet discomposes into energetic plasma ion and neutrals, and slow gas and fragments (the majority of the target material)

Vaporization (static)

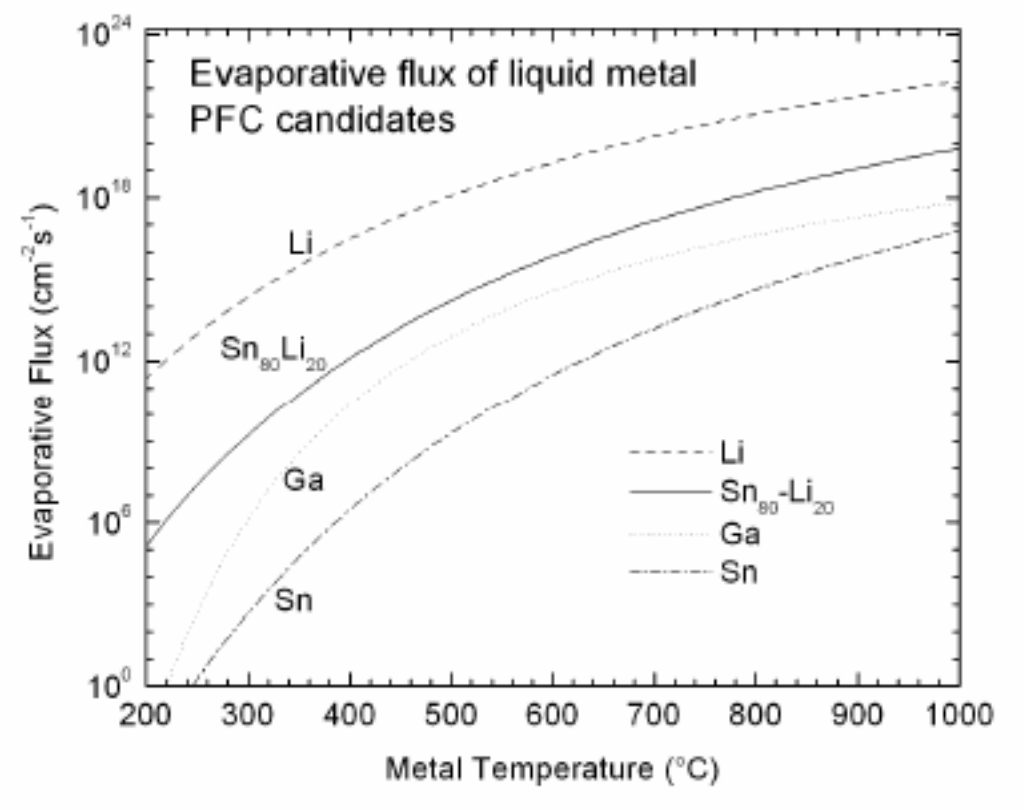


Figure 1. Evaporation flux as a function of surface temperature for four of the primary candidates for liquid metal PFC materials. The curves for Li and $Sn_{80}Li_{20}$ are from [1] while those for Sn and Ga are from [3] and [4], respectively.

10^{-5} atom emission from 20μm droplet during 10cm flight at 60m/s speed

LPP modeling & Warm dense matter

Exact hydrodynamics modeling needs EOS (+ kinetic effects) on whole ablation pathways.

- Binode & spinode: liquid-gas mixture .

(1) Adiabatic expansion with droplets creation after a weak heating.

(2) Adiabatic expansion with partial re-condensation after strong heating.

(3) Adiabatic expansion with a transition into plasma and gas phases.

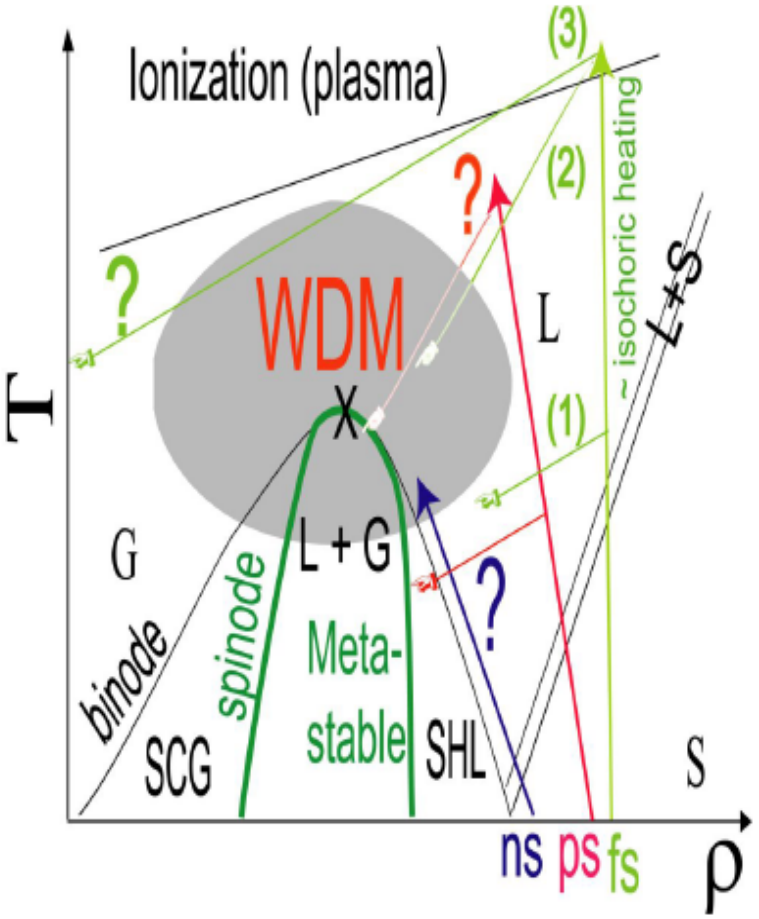
Lescoute, Phys. Plasmas (2008).

Initial stage pass through:

WDM: 0.1 eV ≤ T ≤ 10 eV, 0.01 g/cc ≤ ρ ≤ 10 g/cc

Solid & Liquid Sn: ~ (5-7) g/cc

- Warm + dense → rapid hydrodynamic → transient phenomena.
- Evaporation & condensation kinetics are fast.
- Laser absorption: not well-known.
- Critical parameters: not well-known.



Typical density – temperature space. X: critical point. SHL: superheated liquid. SCG: supercooled gas. ns & ps & fs : typical laser pulse in EUV source.

LPP modeling & Warm dense matter

Superheating (supercooling) is demonstrated for solid and liquid.

Iglev, Nature (2006) & Luo, Phys. Rev. B (2003) & Xu, J. Heat Trans. (2002) & Lewis , Appl. Surf. Sci. (2009).

Thermodynamic (equilibrium stage)

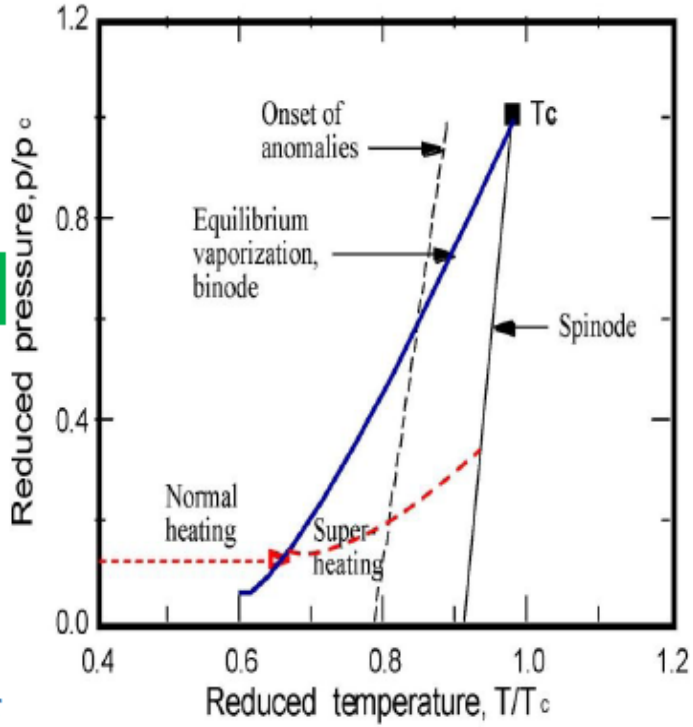
Slow heating → binode → Clausius-Clapeyron equation.

Non-equilibrium (metastable liquid)

High energy deposition → metastable state → phase explosion, spallation, fragmentation

- Pure liquid: homogenous nucleation time ≈ ns.
- Liquid metals: spontaneous nucleation is longer or not realized even for very large superheating (is under investigation by molecular dynamics).

Bulgakova, Appl. Surf. Sci. (2007), etc.

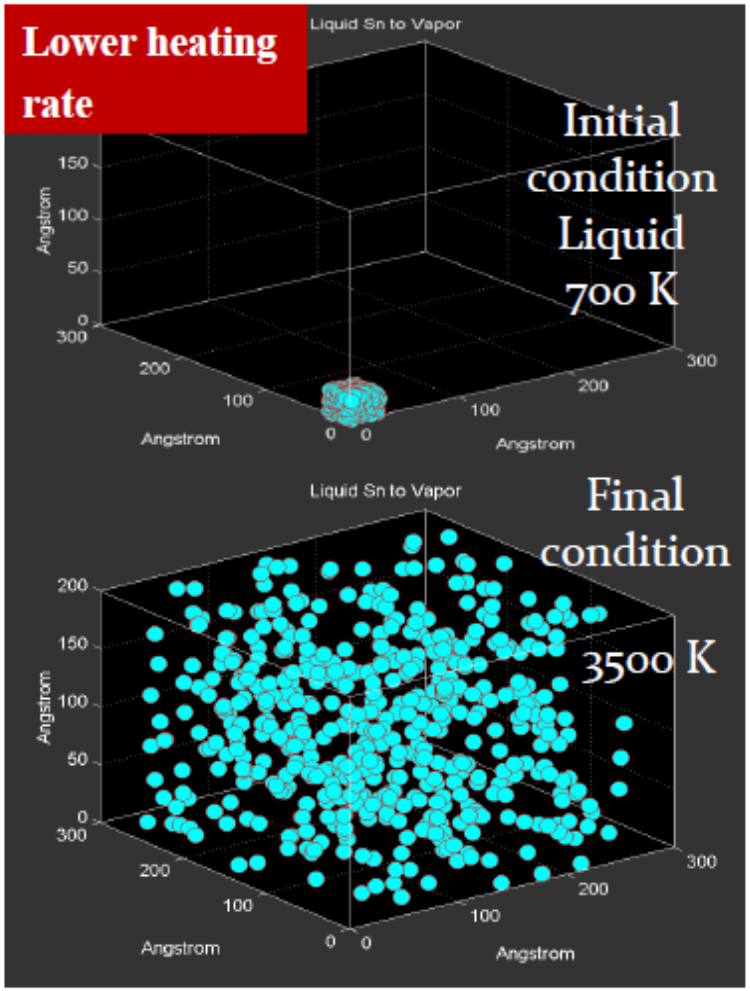


Typical P-T diagram of phase explosion. Dome in solid line is binode. Dome in dashed line is spinode. Tc and pc are critical parameters.

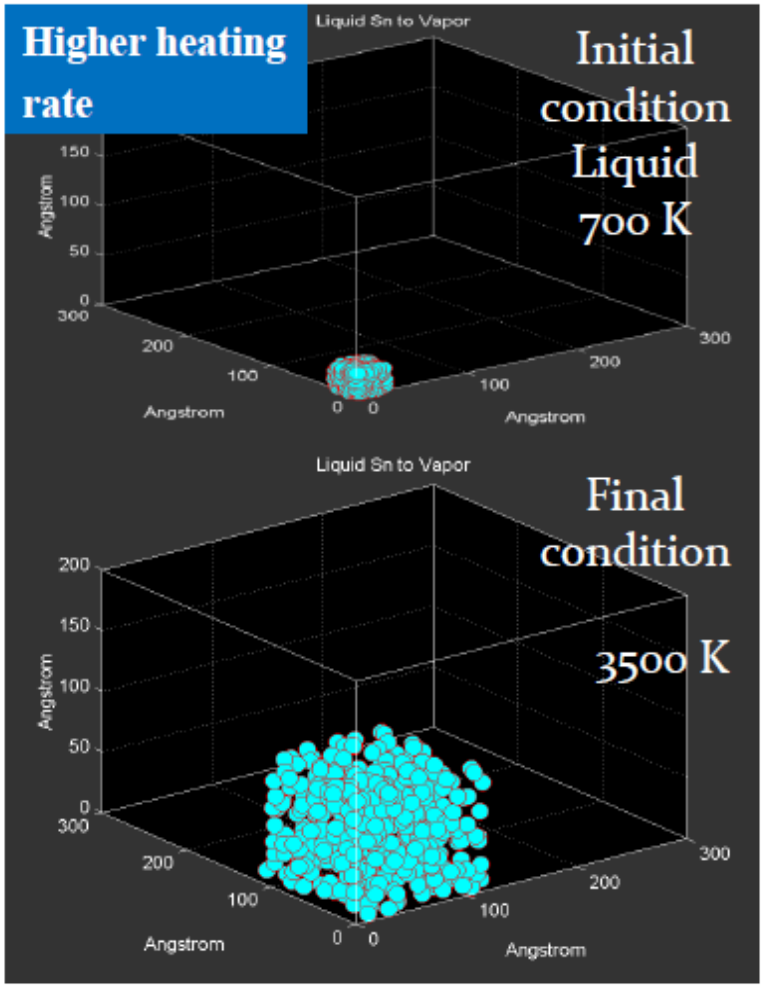
Boiling & Vaporization

Inertial confinement effect

Lower heating rate



Higher heating rate



Thermal history changes the thermodynamic pathways.

JOURNAL OF APPLIED PHYSICS **109**, 123306 (2011)

Simulation of particle velocity in a laser-produced tin plasma extreme ultraviolet source

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[2]*Plasma Physics Research Center, Azad University, Tehran, Iran*

[3]*Friedrich-Schiller University, Institute of Applied Physics, Jena, Germany*

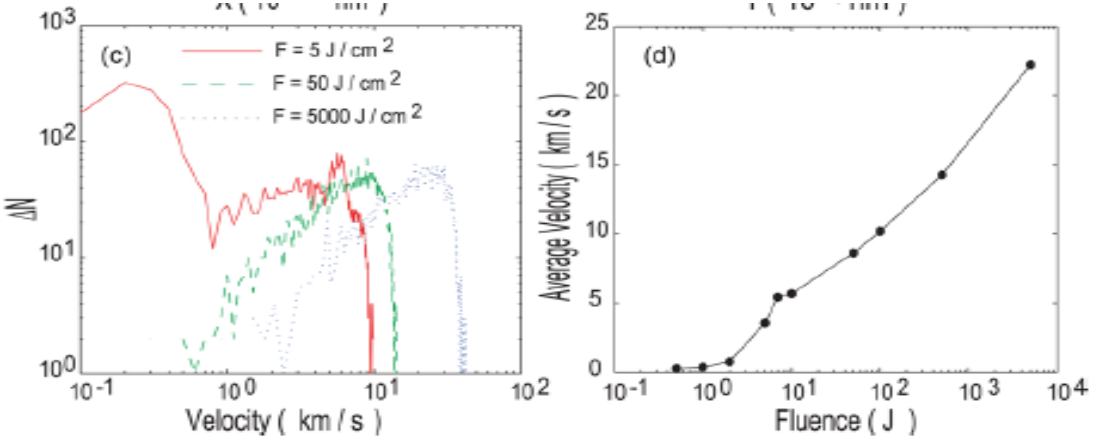
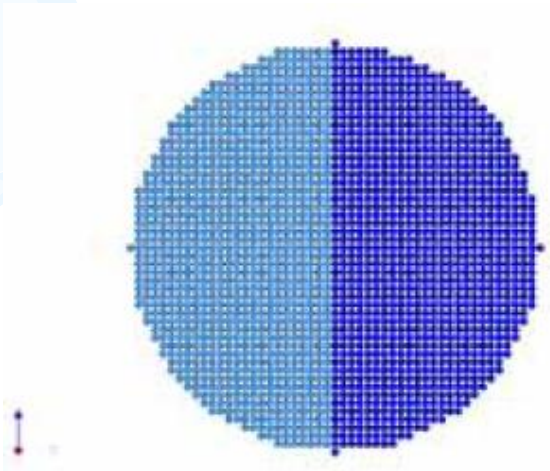


FIG. 6. (Color online) (a) The initial condition is assumed to be a small Sn sample size of $\simeq 2 \times 2 \times 35$ nm. A laser pulse is irradiated from the top surface of the sample. (b) A typical snapshot of particle velocities perpendicular to the laser direction and charge states against the norm of the position vector r before the maximum intensity of a laser pulse with a fluence of 500 J cm^{-2}. (c) The velocity distribution of Sn particles at various fluences of 5, 50, and 5000 J cm^{-2}. (d) The weighted average velocity values versus the laser fluence.

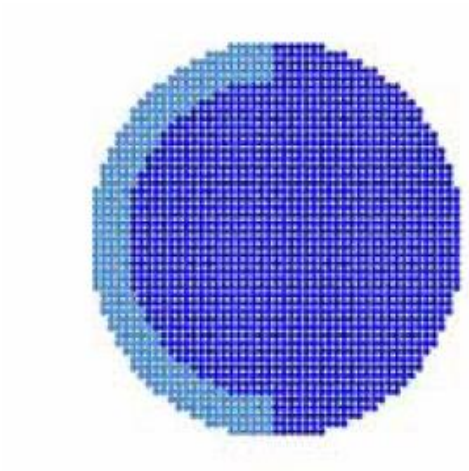
Fluid mechanical simulation of doplet fragmentation

Moving particle semi-implicit method : MPS

100μm Sn droplet with prepulse irradiation

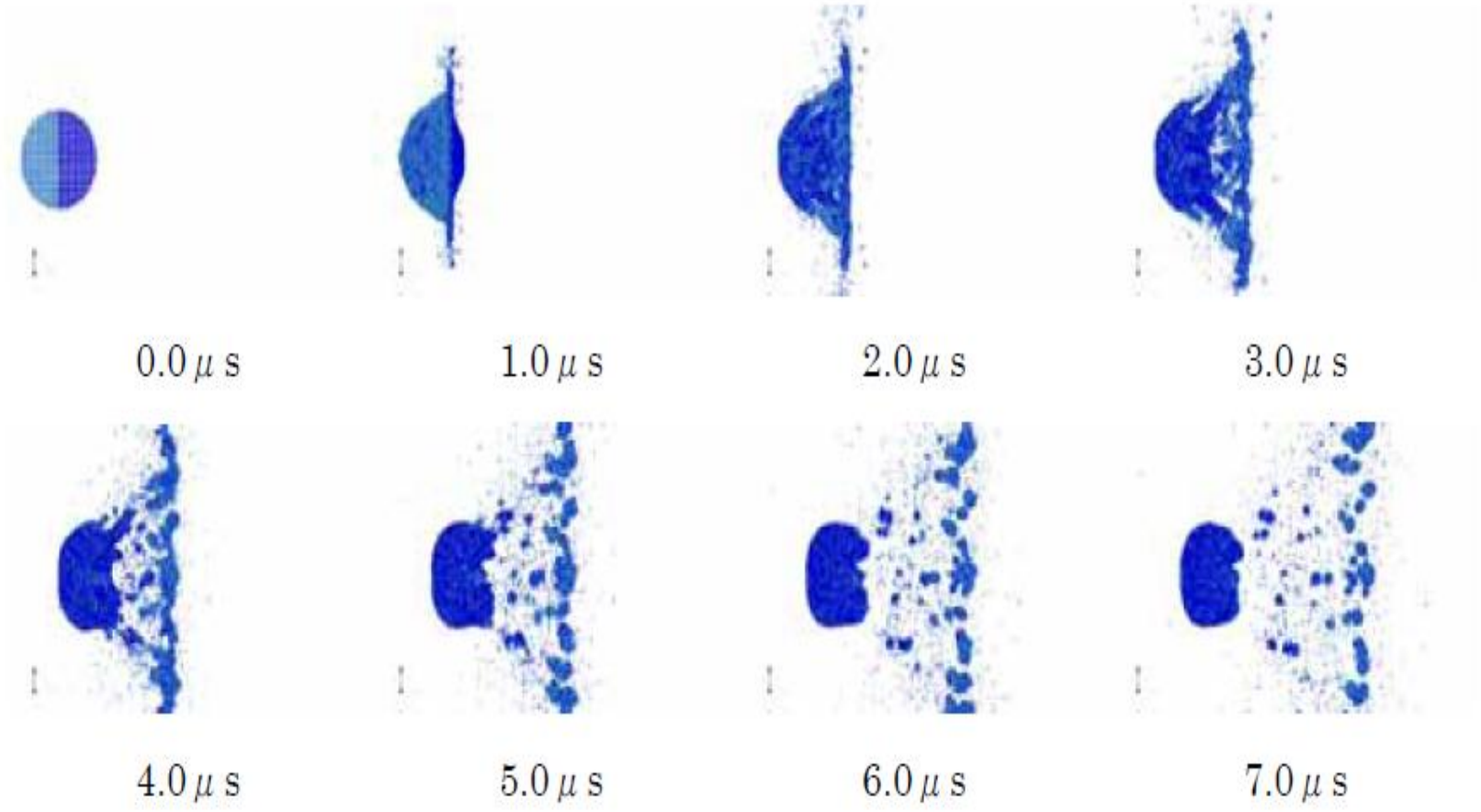


side

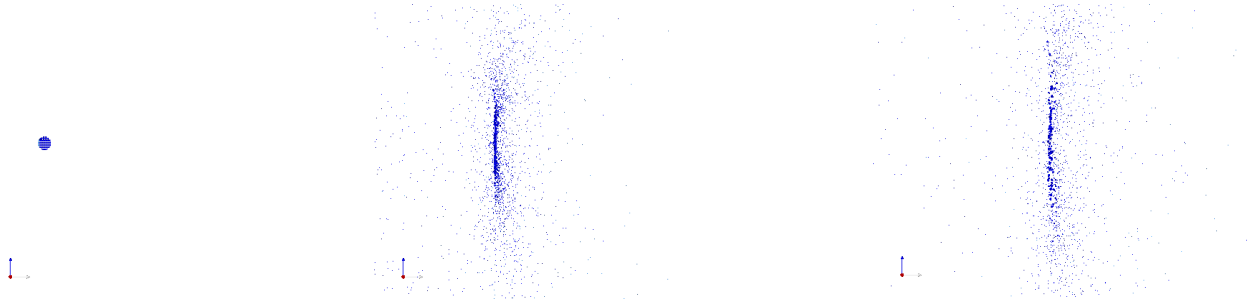


top

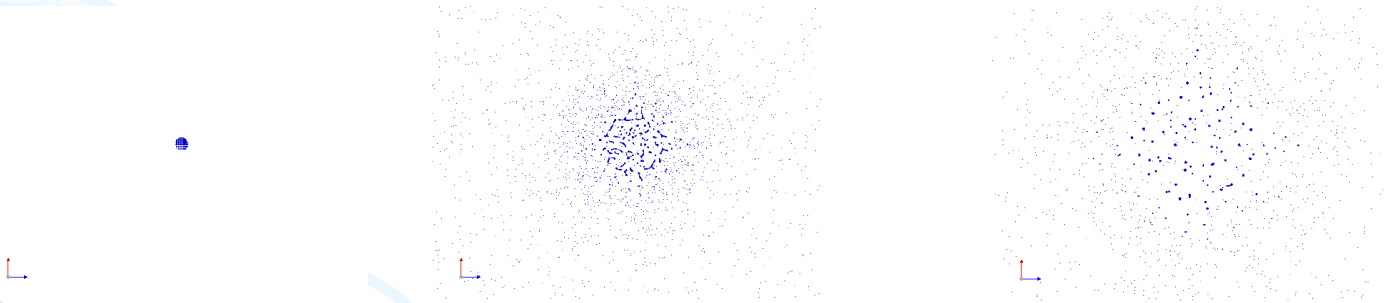
Laser prepulse gives 100μm droplet 15m/s horizontal speed and partial fragmentation



Optimized condition : 10μm droplet with 300m/s speed by prepulse



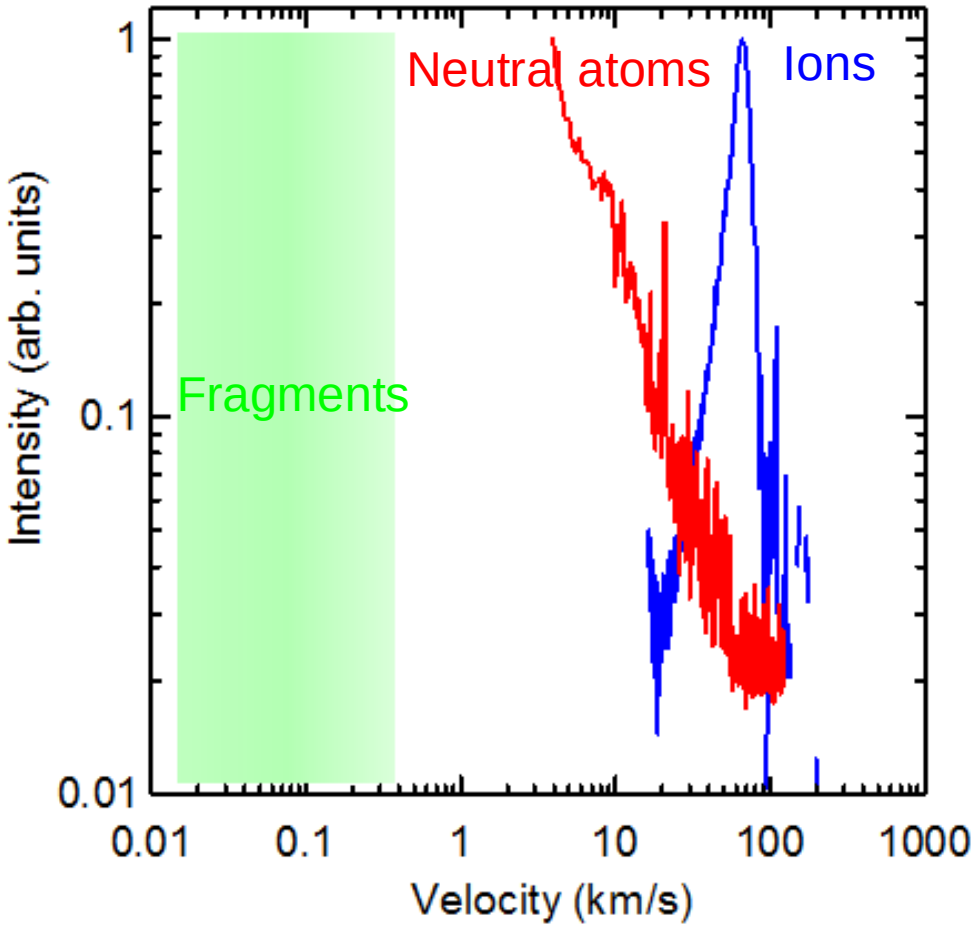
Oblique image



On axis image

Mist generation is realized with 10μm Sn droplet

Measured Speed ; ions, neutrals and fragments



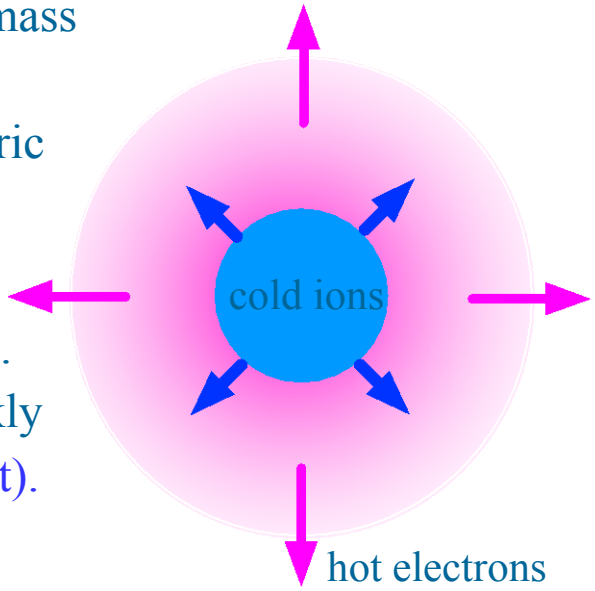
Main pulse irradiation

Plasma expansion is characterized by two phases

At $t = 0$ the electron component of a finite plasma mass is heated to a uniform temperature $T_e(r, 0) = T_{e0}$.
Hot electrons expand and create an ambipolar electric field $E(r, t)$, which drags the cold ions.

Assumptions

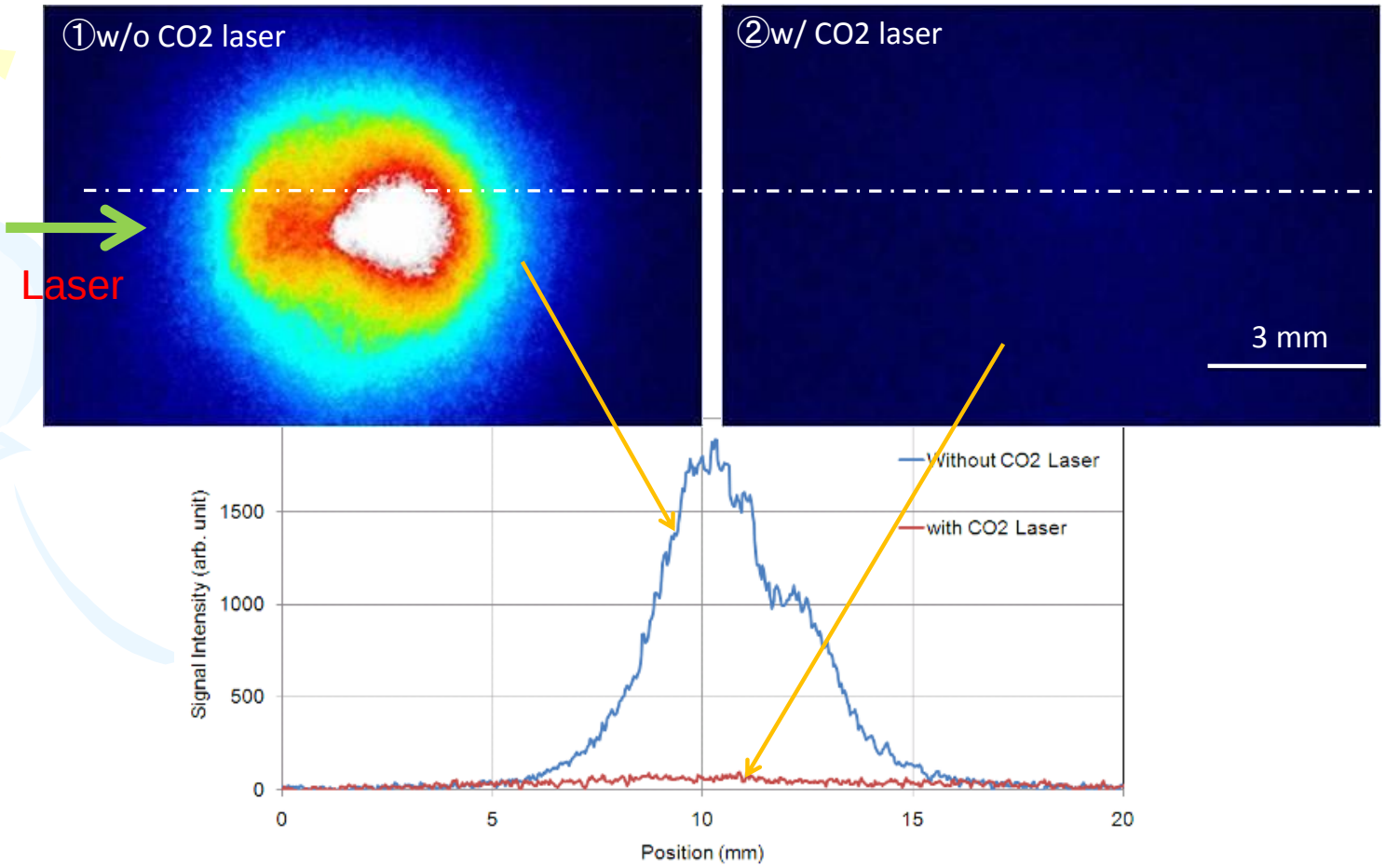
- There are no collisions between electrons and ions.
- At all times, the electron temperature is very quickly leveled off across the plasma volume: $T_e(r, t) = T_e(t)$.



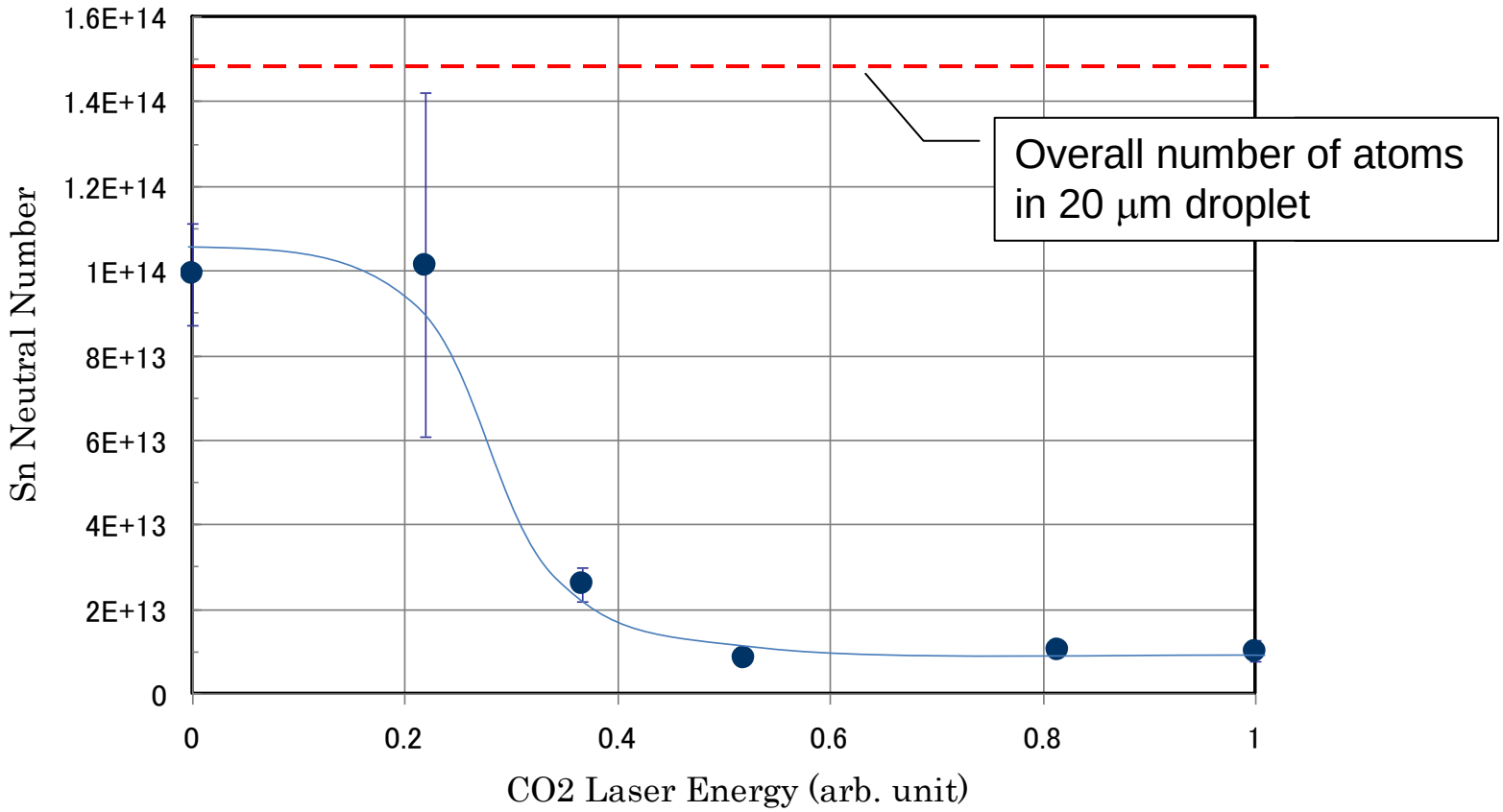
Isothermal phase : during laser irradiation,
Energy spectrum is established

Adiabatic phase : after laser irradiation,
Energy spectrum is unchanged

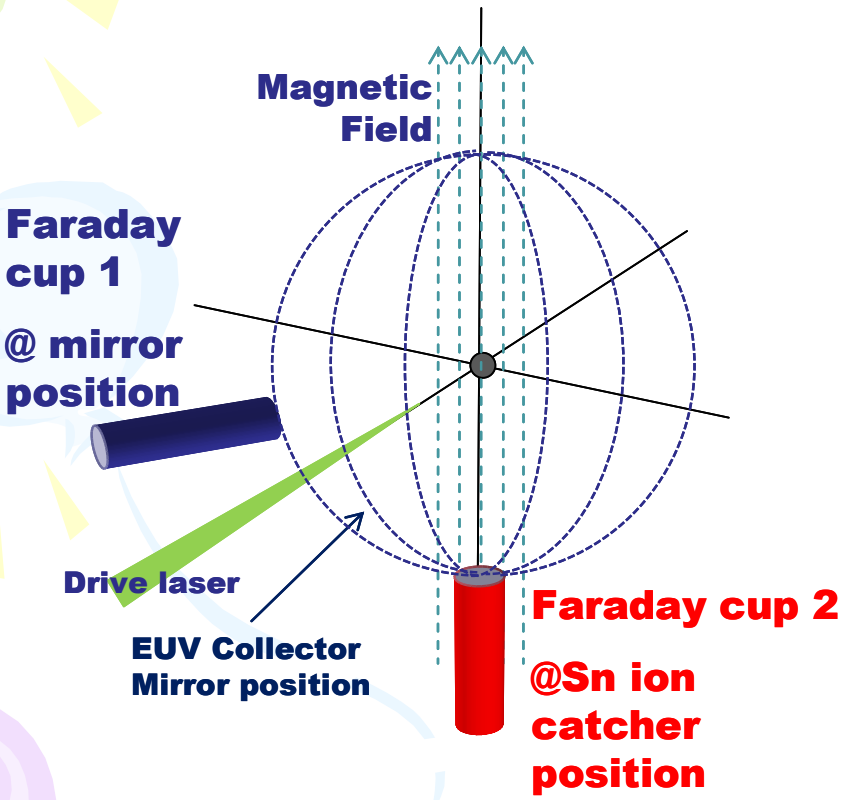
LIF measurements of neutrals in mist target

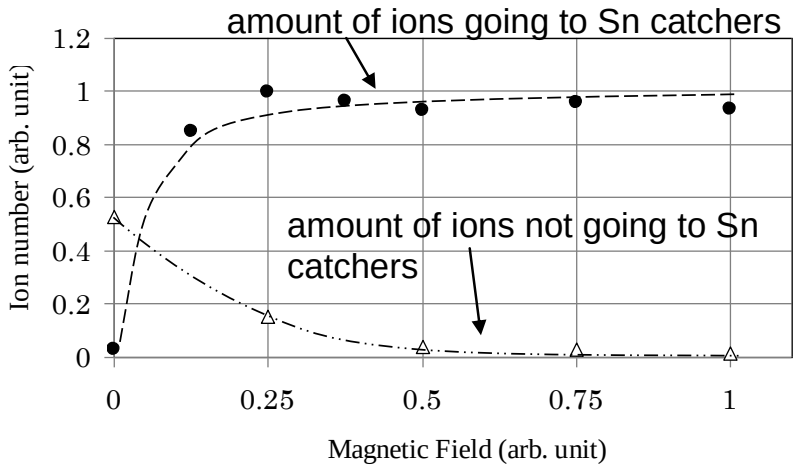


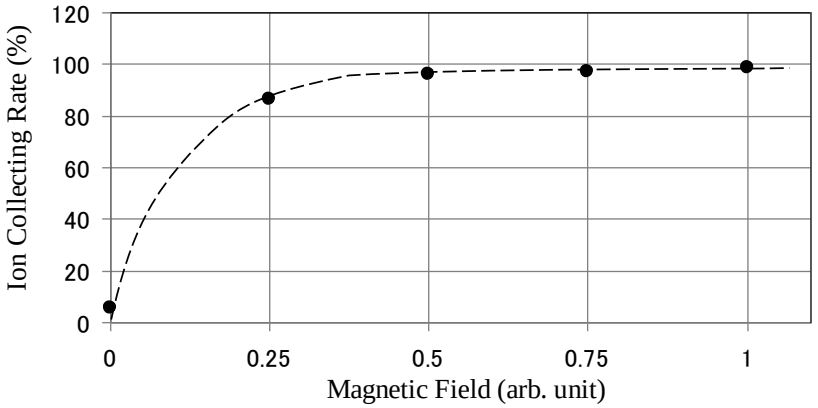
Remaining neutrals



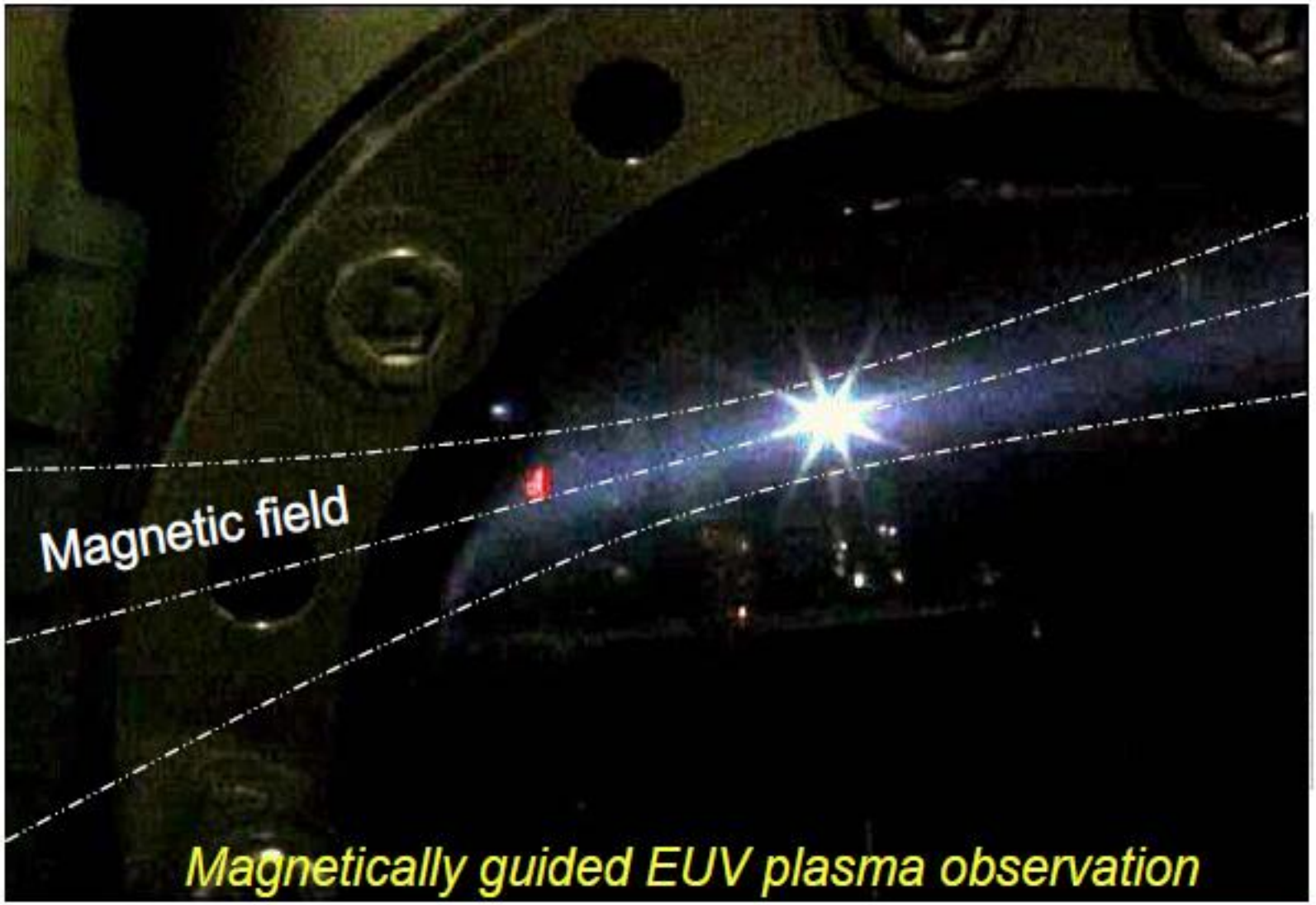
Ion and neutral particle drift in transport magnetic field







Plasma flow from pre-pulsed droplet



Ion flux characterization

- Droplet

 diameter 20 um

- Laser

 CO_2 pulse energy 166 mJ
 Pulse width 20 ns(FWHM)
 Spot size 300um(1/e^2)
 With pre-pulse laser

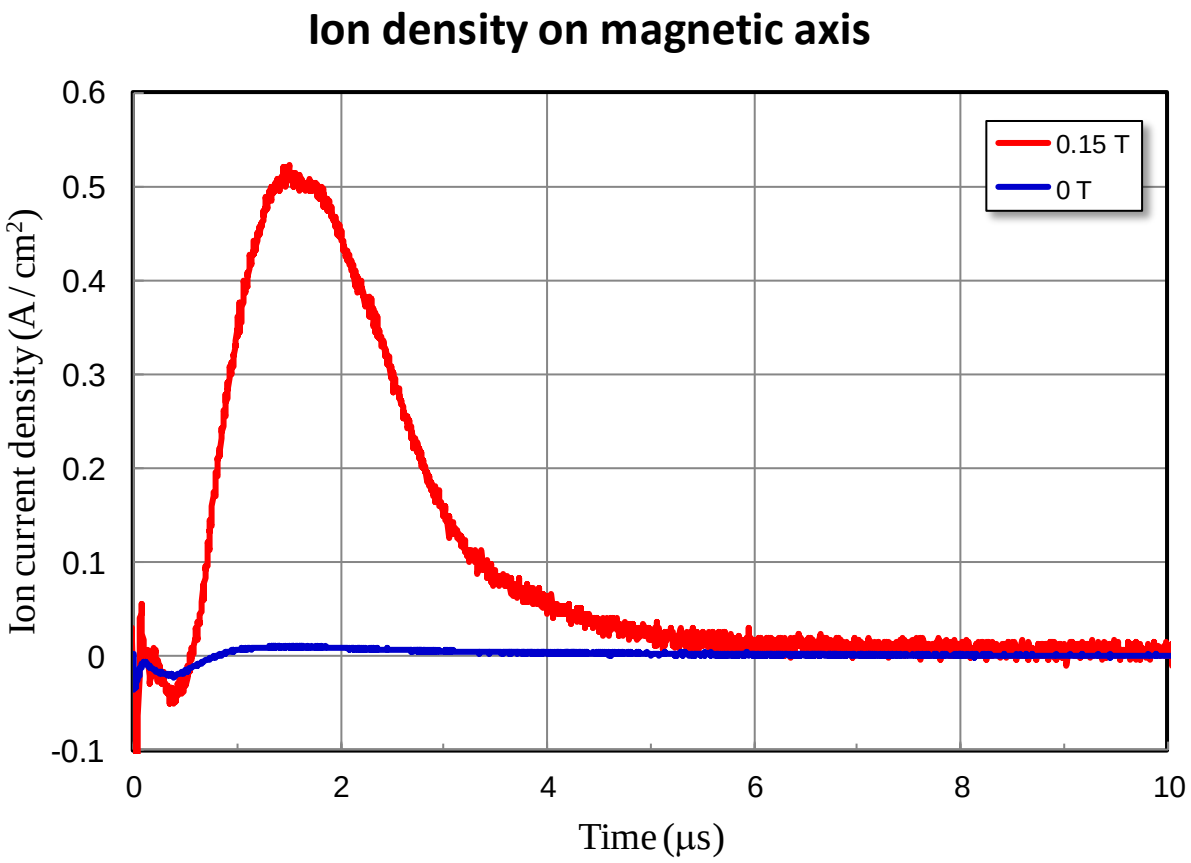
Magnetic field

 0.15 T at center

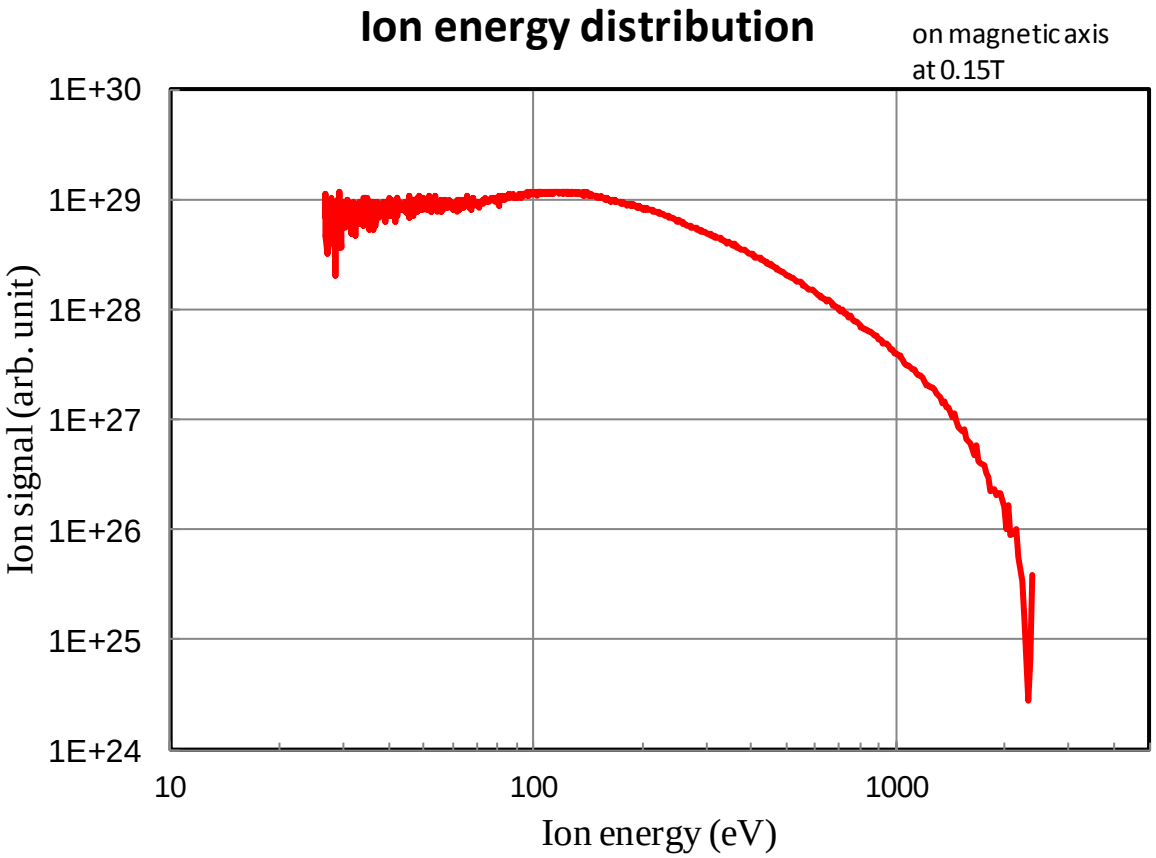
- Faraday cup

 clear aperture 5mmϕ

Measured ion flux at Faraday Cup



Ion Energy Distribution



Conclusion

- Pre-pulse Tin droplet dispersion was well characterized
- Ideal Tin target conditioning was realized by 10μm diameter Tin droplet
- Full ionization was realized by the combination of Tin cluster target and CO_2 laser irradiation
- Ion flux was characterized by Faraday Cup measurement

Total measured charge 2.56^{-5} C

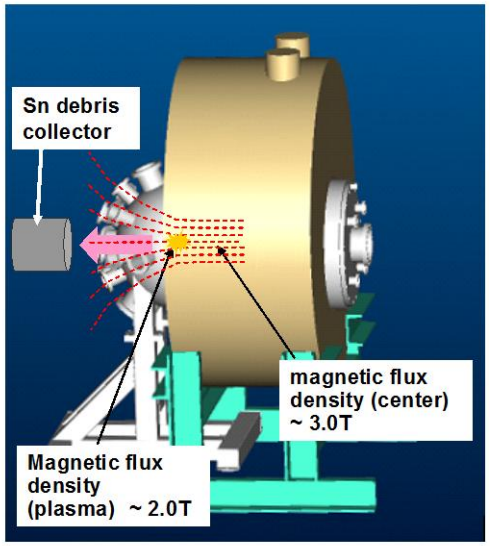
Calculated total charge of $Sn^{+}1$ from 20μm droplet 2.48^{-5} C

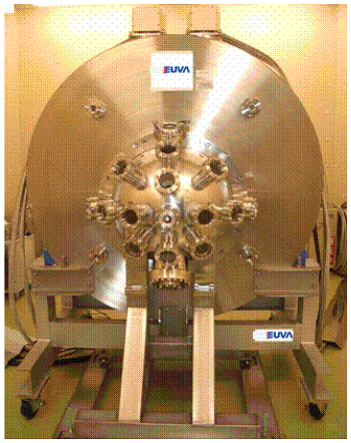
Plasma flow in transport magnetic field

Superconducting magnet was employed

1) Characterization of Sn ion flux

2) Optimization of Sn evacuation.





Visible image of Sn ion flow in magnetic field

Laser : CO2 laser, Target : Sn plate

Without magnetic field

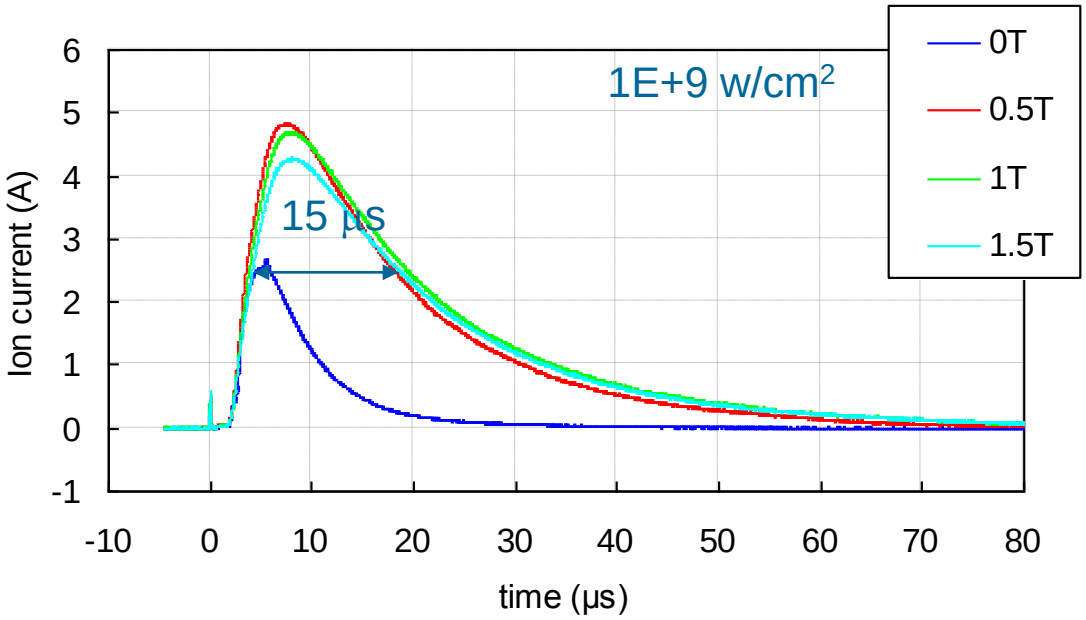


Magnetic field : 2T



Ion current waveform

Typical ion waveforms



Peak ion current : ~ 5 A

Total charge amount : 1E-4 C

At 100kHz ; 10C/s (10 A)

Concept of high current laser ion source

Laser full ionization of metal micro droplet

